Proceedings of the 16th International Conference on Soil Mechanics and Geotechnical Engineering

doi:10.3233/978-1-61499-656-9-779

Viscous property of clay in 1-D compression: Evaluation and modelling

Propriété visqueuse des argiles en compression unidimensionnelle: Evaluation et modélisation

Hugo Acosta Martínez
IGL, Bogota, Colombia. Former University of Tokyo
Fumio Tatsuoka
Department of Civil Engineering, Tokyo University of Science
Jianzhong Li
School of Geoscience and Environment Engineering, Central South University, Changsa, China

ABSTRACT
A series of strain rate-controlled one-dimensional (1D) compression tests were performed on soft and stiff clays to evaluate their viscous properties. The strain rate was changed stepwise many times and several short-term and long-term drained creep loading tests were performed during otherwise monotonic primary loading, unloading and reloading. Viscous effects observed in the experiments and empirical rules derived from them are presented. The test results are simulated by a specific non-linear three-component rheology model, called the New Isotach model, which has been developed to simulate the viscous properties of geomaterial in plane strain and triaxial compression. The model can also reproduce quite well the results from the 1D tests on clays performed in the present study.

RÉSUMÉ
Pendant cette recherche qui portait sur l'évaluation de la propriété visqueuse des argiles, on réalisé d'essais de compression unidimensionnelle sur argiles souples et dures. Le taux de déformation a été modifié subitement à plusieurs reprises et on a réalisé plusieurs déterminations de "creep" de longue et de courte durée dans une condition générale de charge, décharge, et recharge monotoniques, sous forme automatique. On présente les effets visqueux observés lors de ces essais et les règles empiriques obtenues. Ces résultats empiriques ont été simules sous un modèle rhéologique de trois dimensions (New Isotach) développé pour travailler les propriétés visqueuses de géomatériels en déformation planaire et compression triaxiale. Ce modèle peut reproduire de manière satisfaisante les résultat des essais de compression unidimensionnelle sur argiles réalise lors de cette recherche.

1 INTRODUCTION

Current geotechnical design is often based on a displacement-based criterion to keep ground deformation and structural displacements at working loads within an allowable limit assuring serviceability and functionality of a concerned structure during its lifetime. Then, it is required to predict the long term-residual deformation of ground and structural displacement under sustained loads. The conventional approach to this issue assumes that creep due to material viscous property occurs only after the end of primary consolidation (EPC). However, there are many evidences showing that creep starts occurring before EPC, during dissipation of pore water pressure, and the viscous component of settlement could be significant and should be properly considered.

Despite that a great number of researches have been performed on this topic, the relationship between viscous properties observed in different testing methods: e.g., drained triaxial compression (TC) and one-dimensional (1D) compression tests, is not well understood. Moreover, the separation between effects of delayed dissipation of excess pore water pressure and true material viscous effects is sometimes very difficult with clay having a relatively low permeability. Accurate knowledge and understanding of the viscous property of clay, which could be obtained only from advanced laboratory stress-strain tests and further by numerical analysis based on relevant constitutive modelling, is not sufficient.

In view of the above, a series of strain-controlled 1D compression tests were performed on soft and stiff clays were tested. The ageing effects on the viscous property were examined. The viscous properties were evaluated by changing stepwise the strain rate many times and performed drained creep tests during otherwise primary loading, unloading and reloading. The test results were analysed and simulated by a non-linear three-component rheology model.

2 TEST METHOD

Five clay types, listed in Table 1, were used. Undisturbed samples of the following Pleistocene clays were tested: Kitan clay retrieved by thin wall tube sampling at a site along the east coast of Awaji Island at the south mouth of Osaka Bay (Komoto et al. 2003; Yamamoto et al. 2003); Ohi-machi clay obtained by block sampling from a deep excavation in the South-eastern part of Tokyo; and Pisa clay (Di Benedetto et al. 2005). Their reconstituted specimens and reconstituted specimens of Fujinomori clay and kaolin were also used. Finally, specimens of initially air-dried and oven-dried Fujinomori clay and oven-dried ones of kaolin were prepared by compacting clay powder inside the oedometer ring.

Table 1: Physical properties of tested clays

Clay type	Gs	D_{50} (mm)	w_L (%)	w_P (%)
Kitan	2.69	0.0034	54.7	13.6
Ohi-machi	2.72	0.0024	42.9	23.0
Fujinomori	2.69	0.017	62.0	29.0
Pisa	2.75	0.0015	77.2	34.3
Kaolin	2.67	0.0013	79.6	38.0

Large cakes of reconstituted clays were prepared by one-dimensional consolidation of well de-aired slurry for a period three times longer than that at EPC in a large oedometer with an inner diameter of 20 cm and an inner height of 60 cm. The normal stress σ_v' was equal to 70 kPa for Fujinomori clay and 200 kPa (similar to the field effective vertical stress) for Kitan clay. σ_v'= 70 kPa was also used for Ohi-machi and Pisa clays for a comparison purpose. The slurry was made by mixing the respective material, sieved in mesh No. 35, with an initial water content that was twice the liquid limit. It was observed that an increase in the time of mixing reduces the heterogeneity in the grain-size distribution along the height in each cake.

The loading rate effects on the stress-strain behaviour of geomaterials are best described in terms of strain rate (more rigorously irreversible strain), rather than stress state (Tatsuoka et al., 2000). For this reason, stress rate-controlled tests are not relevant to evaluate the stress-strain behaviour as a function of strain rate. In particular, when approaching the peak stress-state, the strain rate increases at a largely increasing rate, making data very difficult to analyse. On the other hand, strain rate-controlled tests are relevant to evaluate the yielding point and the preconsolidation pressure in an objective manner. In the present study, the following two set of 1D compression apparatuses were used.

(a) An oedometer apparatus with an air-cylinder for axial loading, used to study long-term creep deformation and its effects on subsequent behaviour by performing constant-rate-of-strain (CRS) tests with intermediate drained creep loading using a specific control software.

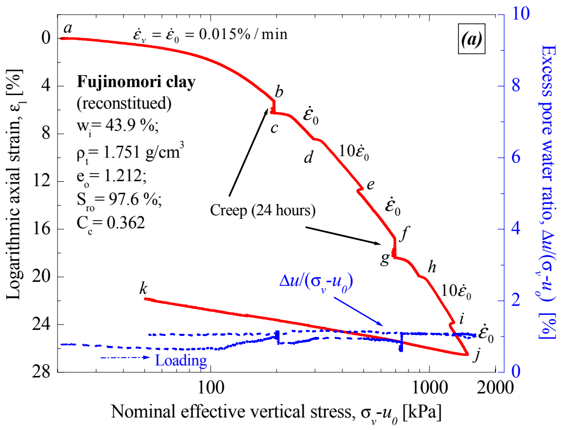
(b) A triaxial apparatus with a precision-gear system for axial loading (Santucci de Magistris et al. 1999), used to perform CRS tests with step changes in strain rate during otherwise monotonic loading (ML) were performed on saturated specimens with drainage from the top of specimen and the pore water pressure measured at the bottom of specimen.

The specimen diameter was 60 mm and the initial height was 20 mm. The initial *D/H* ratio, 3.0, was only slightly larger than 2.5 that is recommended in several test standards to reduce side wall friction effects. The inner wall of the ring was smeared with grease to reduce side friction. The drainage path in test *(b)* was twice when compared with test *(a)*. Vertical strains from displacements of the loading piston, corrected for system compliance, bedding error and compression of filter paper (one sheet at each end), and the averaged effective vertical stress, σ'_v, of the specimen are presented below.

3 TEST RESULT

Figure 1 shows typical relationships between the nominal effective vertical stress, $\sigma'_v = \sigma_v - u_0$, and the axial strain (logarithmic) of saturated specimens of Fujinomori, Ohi-machi and Kitan clays. The following trends may be seen:

1) Except when σ'_v was larger than about 230 kPa in the test on Ohi-machi clay, in which the axial strain rate was much higher than the other two tests, the excess pore pressure Δu was always negligible when compared to σ'_v. This result show that the specimens were always under nearly fully saturated conditions.
2) The σ'_v value changed stepwise upon a step change in the strain rate, while significant creep strains developed. These rate-dependent behaviours are due essentially to the material viscous property of clay, as observed in drained TC tests of clay (e.g., Li et al. 2003; Komoto et al. 2003).



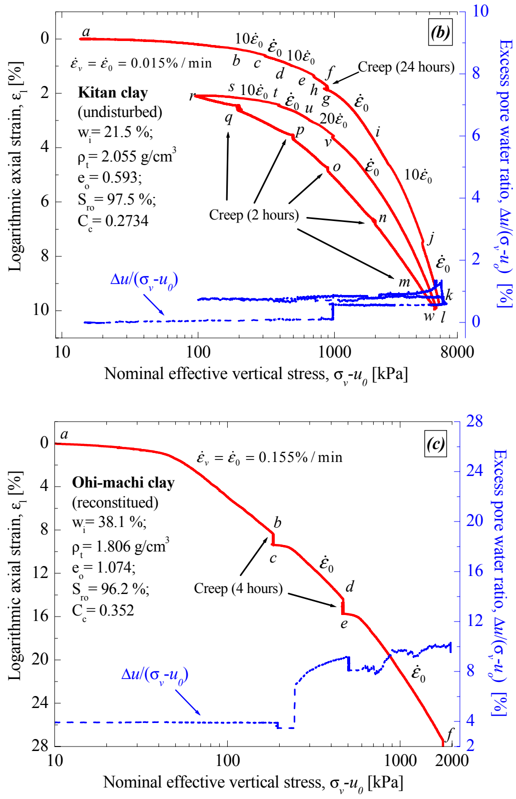


Figure 1. Typical stress-strain relationships: *a)* reconstituted Fujinomori clay; *b)* undisturbed Kitan clay, and; *c)* reconstituted Ohi-machi clay.

Figure 2 shows the result from a typical test in oven-dried Fujinomori clay, indicating the water content measured after the test. Noticeable loading rate effects can also be seen, which are due totally to the material viscosity.

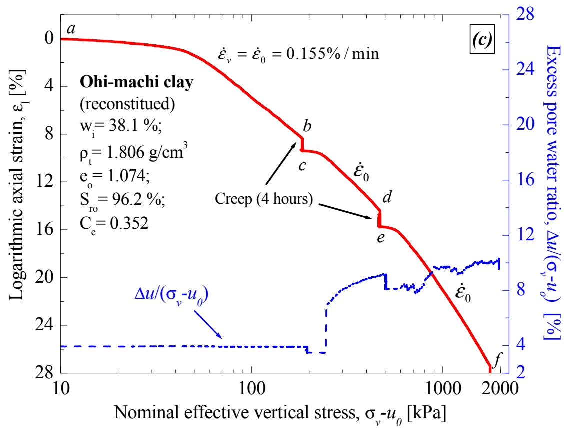


Figure 2. 1-D stress-strain relation of compacted oven-dried Fujinomori clay.

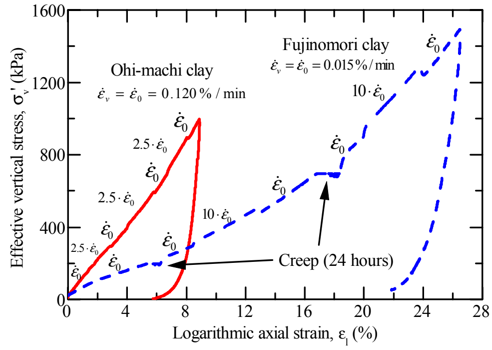


Figure 3. Typical test results showing a trend of *Isotach* viscosity.

As typically shown in Figure 3, the clay specimens exhibit commonly the so-called Isotach viscosity; i.e., different stress-strain relations develop by ML at different constant strain rates, while the present stress is always a unique function of instantaneous irreversible strain and its rate.

To compare the viscous properties of different clay types, the difference in the stress values after and before a sudden change in the irreversible strain rate, $\dot{\varepsilon}_v$, both defined for the same irreversible strain, $\Delta\sigma'_v = (\partial\sigma'_v / \partial\dot{\varepsilon}^{ir}_v)\cdot\Delta\partial\dot{\varepsilon}^{ir}_v$ (Figure 4), was obtained. In Figure 4, curve *c-d* is drawn so that the σ'_v value along curve *c-d* is proportional to that value along curve *a-b* at the same value of ε^{ir}_v. The instantaneous elastic modulus E^e used in this analysis was obtained by the method described in Tatsuoka and Kohata (1995): $E^e = \partial\sigma'_v / \partial\varepsilon^e_v = (E_v)_0 \cdot (\sigma'_v / \sigma_0)^m$, where $(E_v)_0$ is the value of E_v when σ'_v is equal to the reference effective pressure σ_0; and m is a power, which was assumed to be equal to 0.5.

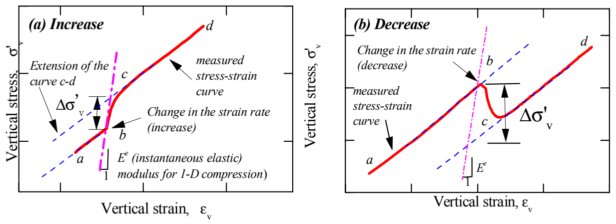


Figure 4. Evaluation of viscous property by strain rate.

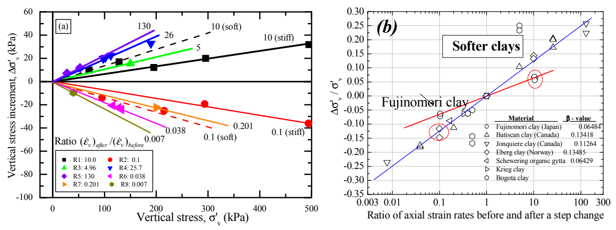


Figure 5. Viscous property of Fujinomori clay and other softer clays.

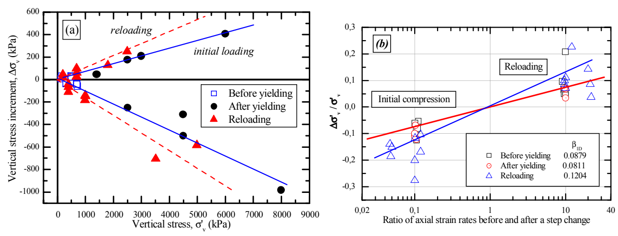


Figure 6. Viscosity of Kitan clay.

In Figures 5a for Fujinomori and Kitan clays, the respective value of $\Delta\sigma'_v$ is plotted against σ'_v. It may be seen that $\Delta\sigma'_v$ is always proportional to σ'_v for the same value of $(\dot{\varepsilon}_v)_{after} / (\dot{\varepsilon}_v)_{before}$, which is essentially the same as $(\dot{\varepsilon}^{ir}_v)_{after} / (\dot{\varepsilon}^{ir}_v)_{before}$. In Figures 5b & 6b, the ratio $\Delta\sigma'_v / \sigma'_v$ is plotted against $\log\{(\dot{\varepsilon}_v)_{after} / (\dot{\varepsilon}_v)_{before}\}$ (together with data of softer clays in Fig. 5b). The relation for the respective strain rate jump is very linear with a slope β (called the rate-sensitivity coefficient). It may be seen by comparing these figures that stiffer clays have lower values of β when compared with soft clay. The effects of the degree of saturation are described in Li et al. (2004).

In the test described in Figure 1b, the strain rate was changed stepwise during otherwise monotonic reloading after large deformation had taken place during the primary loading followed by global unloading. The slope β during reloading was noticeable larger that the value during primary loading (Figure 6b). It seems that the structure of clay was damaged by large deformation during primary loading, which resulted in an increase in β during reloading, especially at its initial stage. After the yield stress was exceeded during reloading, the slope β became similar to the value during the first primary loading.

The creep strain was substantially larger during the primary loading than during the subsequent reloading at the same stress level. Furthermore, the creep strain rate was essentially proportional to the strain rate at the start of creep loading.

The creep behaviour during global unloading was examined in cases *a)* with and *b)* without allowing the specimen to exhibit creep deformation at the maximum stress before the start of unloading (Figure 7). In case *a)*, the creep strain during global unloading became negative already after a relatively small amount of stress unloading. On the other hand, in case *b)*, the creep strain rate was still positive after some stress unloading. These results indicate that loading and unloading can be defined only by the sign of irreversible strain rate. In these figures, the primary stress-strain relation along which the creep strain rate would be zero (called the reference curv) is depicted.

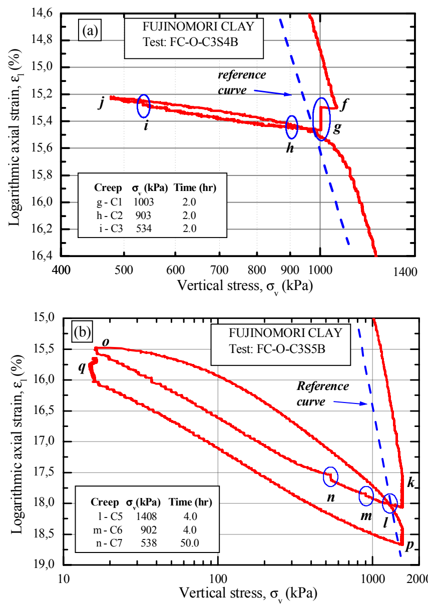


Figure 7. Viscous behaviour during unloading: a) without previous creep, and; b) with previous creep.

4 SIMULATION

According to the conventional Isotach model, the stress σ during ML is a unique function of instantaneous total strain ε and its rate $\dot{\varepsilon}$, irrespective of strain history. However, as the elastic properties are independent of strain rate, the time effects should be represented in terms of irreversible strain rate $\dot{\varepsilon}^{ir}$ ($= \dot{\varepsilon}$ - elastic strain rate $\dot{\varepsilon}^e$). Other drawbacks of the Isotach model are: stress relation behaviour at a fixed total strain cannot be simulated, and the stress-strain behaviour upon a step change in $\dot{\varepsilon}$ cannot be simulated either.

Tatsuoka et al. (1999, 2001) showed that, with geomaterials, the stress σ is basically a unique function of instantaneous irreversible strain ε^{ir} and its rate $\dot{\varepsilon}^{ir}$. Based on this fact, Di Benedetto et al. (2002) and Tatsuoka et al. (2002) proposed the so-called New Isotach model (Fig. 8). h_1 and h_2 in Figure 8 are the parameters to describe the effects of stress history.

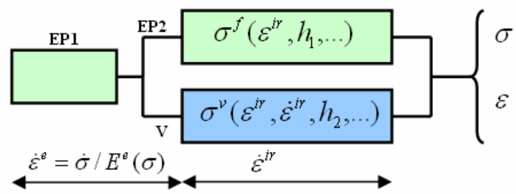


Figure 8. Structure of three-component model (Di Benedetto et al. 2002)

With the New Isotach model, in ML case, the total stress σ is decomposed into the inviscid and viscous components:

$$\sigma = \sigma^f(\varepsilon^{ir}) + \sigma^v(\varepsilon^{ir}, \dot{\varepsilon}^{ir}) \tag{1}$$

Tatsuoka et al. (2001) showed that the following is relevant:

$$\sigma^v(\varepsilon^{ir}, \dot{\varepsilon}^{ir}) = \sigma^f(\varepsilon^{ir}) \cdot g_v(\dot{\varepsilon}^{ir}) \tag{2}$$

$$\sigma = \sigma^f(\varepsilon^{ir}) + \sigma^v(\dot{\varepsilon}^{ir}) = \sigma^f(\varepsilon^{ir}) \cdot \{1 + g_v(\dot{\varepsilon}^{ir})\} \tag{3}$$

$g_v(\dot{\varepsilon}^{ir})$ is the viscosity function, given as:

$$g_v(\varepsilon^{ir}) = \alpha \cdot [1 - \exp\{1 - (\frac{\dot{\varepsilon}^{ir}}{\dot{\varepsilon}_r^{ir}})^m\}](\geq 0) \tag{4}$$

where α, m and $\dot{\varepsilon}_r^{ir}$ are the material parameters that control the viscous property. Then, different stress-strain curves will be obtained for monotonic loading at different strain rates. The parameters can be determined so that the relation $\log[1 + g_v(\varepsilon^{ir})] - \log[\dot{\varepsilon}^{ir}]$ have a slope $b = \beta/\ln 10$.

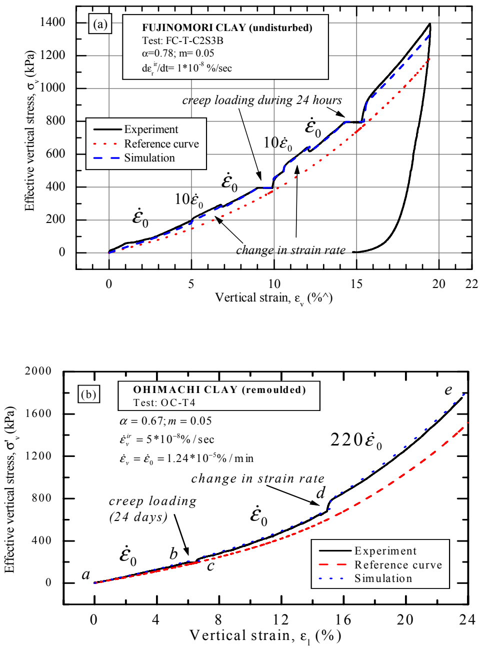


Figure 9. Typical test result and their simulation.

A simple methodology was applied to define the reference stress-strain relation, not including any viscous effects. That is, it was assumed that the stress of the reference curve is proportional to the value of the stress-strain curve fitted to the measured stress-strain curve obtained by ML at a fixed strain rate. The respective reference curve was fitted by using a polynomial regression in the form $Y=A+B_1X+B_2X_2+B_3X_3+ \ldots + B_KX_K$. In tests in which long-creep loading stages with duration of one week were applied, the end point of the creep stage helped to define the proportional factor, because the reference curve should be located near the end of creep loading.

Figure 9 shows two typical simulations by the New Isotach model. Both magnitude of creep strain, as well as the amount of jump in the vertical stress after a sudden change in the strain rate obtained are well simulated.

5 CONCLUSIONS

The following conclusions can be derived from the results of the 1D compression tests on clay and their analysis:

1) The stress was essentially a unique function of instantaneous irreversible strain and its rate. This is consistent with the observations of Tatsuoka et al. (1999, 2001) on other types of geomaterials under stress conditions other than 1-D compression.
2) The stress change upon a step change in the strain rate was always proportional to the instantaneous stress. Based on this fact, the relation $\Delta\sigma'_v/\sigma'_v = \beta\{(\dot{\varepsilon}_v^{ir})_{after}/(\dot{\varepsilon}_v^{ir})_{before}\}$, where β is the rate-sensitivity coefficient, can be proposed to express the viscous property. The relation was relevant for reconstituted, remoulded and undisturbed clays, while the β value was smaller with stiffer clays.
3) A non-linear three component model, which incorporates the rate-sensitivity coefficient β and an inviscid stress-strain relation, was found relevant to simulate the rate effects observed in the present study.

ACKNOWLEDGEMENTS

All the authors express their gratitude for previous colleagues and staff of the Geotechnical Engineering Laboratory, Department of Civil Engineering, University of Tokyo, Japan.

REFERENCES

Di Bennedetto, H., Tatsuoka, F. and Ishihara, M. (2002). Time-dependent deformation characteristics of sand and their constitutive modelling, *Soils and Foundations*, 42-2, pp. 1-22.

Di Benedetto, H., Tatsuoka, F., Lo Presti, D., Sauzéat, C. and Geoffroy H. (2004). Time effects on the behaviour of geomaterials, Keynote Lecture, *Proc. 3rd Int. Sym. on Deformation Characteristics of Geomaterials* (Di Benedetto et al. eds.), Balkema, Vol.2.

Komoto, N., Nishi, T., Li, J. Z. and Tatsuoka, F. (2003). Viscous stress-strain properties of undisturbed Pleistocene clay and its constitutive modeling, *Proc. 3rd Int. Sym. on Deformation Characteristics of Geomaterials*, IS Lyon 03 (Di Benedetto et al. eds.), Balkema, September, 2003, pp.579-587.

Lansivaara, T. and Nordal, S. (2000). "Strain rate approach to creep evaluations", *Proc. NGM - 2000 Nordiska Geoteknikermötet*, 13, Helsinki, June, pp. 25-32.

Lerouiel, S., and Marques, M.E.S. (1996). "Importance of strain rate and temperature effects in geotechnical engineering" *Proc. Measuring and Modeling Time Dependant Soil Behavior, Geotechnical Special Publication No. 61* (Sheanan & Kaliakin, eds.), ASCE, Reston, Va., pp. 1-60.

Leroueil, S., Perret, D., and Locat, J. (1996). Strain rate and structurating effects on the compressibility of a young clay" *Proc. Measuring and Modeling Time Dependant Soil Behavior, Geotechnical Special Publication No. 61* (Sheanan & Kaliakin, eds.), ASCE, Reston, Va., 137-150.

Li, J. Z., Tatsuoka, F., Nishi, T. And Komoto, N. (2003). Viscous stress-strain behaviour of clay under unloading conditions, *Proc. 3rd Int. Sym. on Deformation Characteristics of Geomaterials*, IS Lyon 03 (Di Benedetto et al. eds.), Balkema, September, 2003, pp.617-625.

Li. J. Z., Acosta-Martínez, H., Tatsuoka, F. And Deng, J.-L. (2004). Viscous property of soft clay and its modeling, Engineering Practice and Performance of Soft Deposits, Proc. of IS-Osaka 2004.

Niemunis, A. and Krieg, S. (1996). Viscous behaviour of soil under oedometric conditions, Can. Geotechnical Journal, 33, pp. 159-168.

Santucci de Magistris,F., Koseki,J., Amaya,M., Hamaya,S., Sato,T. and Tatsuoka,F. (1999), "A triaxial testing system to evaluate stress-strain behaviour of soils for wide range of strain and strain rate", *Geotechnical Testing Journal, ASTM,* 22-1, pp.44-60.

Tatsuoka,F. and Kohata,Y. (1995), "Stiffness of hard soils and soft rocks in engineering applications", *Keynote Lecture, Proc. of Int. Symposium Pre-Failure Deformation of Geomaterials* (Shibuya et al., eds.), Balkema, Vol. 2, pp.947-1063.

Tatsuoka,F., Santucci de Magistris,F. and Momoya,M. and Maruyama,N. (1999): Isotach behaviour of geomaterials and its modelling, *Proc. Second Int. Conf. on Pre-Failure Deformation Characteristics of Geomaterials, IS Torino '99* (Jamiolkowski et al., eds.), Balkema, Vol.1, pp.491-499.

Tatsuoka, F., Uchimura, T., Hayano, K., Di Benedetto, H., Koseki, J. and Siddiquee, M.S.A. (2001); Time-dependent deformation characteristics of stiff geomaterials in engineering practice, the Theme Lecture, *Proc. of 2nd Int. Conf. on Pre-failure Deformation Characteristics of Geomaterials, Torino, 1999, Balkema* (Jamiolkowski et al., eds.), Vol. 2, pp.1161-1262.

Tatsuoka, F., Ishihara, M., Di Benedetto, H. and Kuwano, R. (2002). Time-dependent compression deformation characteristics of geomaterials and their simulation, *Soils and Foundations*, 42-2, pp.103-129.